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Comparison of Control Strategies of DSTATACOM for Non-linear Load Compensation

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***Abstract*— For load compensation a number of control strategies have been developed by researchers but choice of control strategy is important to cope with the operating condition of system. In this paper five control strategies viz. instantaneous p-q theory, synchronous reference frame Method(SRF), Modified SRF Method(MSRF), instantaneous symmetrical component theory(ISCT) and Average unit power factor theory(AUPFT) are compared for different two conditions. The performance of the system simulated in Matlab Platform and evaluated considering the source current total harmonic distortion. The result shows Modified SRF(id-iq) Method has improved system performance as compared to others.**

***Index Terms*— Modified SRF, SRF, p-q , ISCT, AUPFT.**

I. INTRODUCTION

During the last decade, there has been sudden increase in the nonlinear load(Computers, Laser printers,SMPS, Rectifier etc.), which degrades the power quality causing a number of disturbances e.g. heating of home appliances , noise etc in power systems[1], [2] due to harmonics.

To compensate the harmonics due to nonlinear load, a Distribution STATicCOMpensator (DSTATCOM) [3] is used. The performance of DSTATCOM largely depends on the control strategies used for reference current current extraction. The control strategy used conventionally, were based on active and reactive power are found unsuitable for unbalance and harmonic conditions. Significant contribution for development of control algorithm was made by Budeanu and Fryze. They provide power definition in frequency and time domain and set the pathways for development universal set power definitions which led to the development of p-q theory by Akagi [4].

In this paper performance of five control strategies such as instantaneous p-q theory, instantaneous symmetrical component theory, SRF Method, Modified SRF Method and AUPF theory are investigated in **three phase three wire system** for balanced source and nonlinear balanced and unbalanced Load.The measures of the performance is the source current total harmonic distortion The results obtained show that under normal operating condition all control strategies are suitable for compensation. But as the operating condition deteriorates the performance of some control strategies degrades.

Rest of the paper is organized as follows. In section II system configuration and in section III brief discussion on different control theories/methods are presented. In section IV the performance indices used for evaluation are discussed. Simulation results are described in section V. Finally in section VI , conclusion are drawn.

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II. System configuration

Fig.1 shows the basic circuit diagram of a DSTATCOM system with non-linear and linear load connected to three phase three wire distribution system. A nonlinear load is realized by using a three phase full bridge diode rectifier whereas linear load is actualized by using resistive- inductive load to make the system balanced or unbalanced. A three phase voltage source converter (VSC) working as a DSTATCOM is realized using six insulated gate bipolar transistor (IGBTs) with anti-parallel diodes. At ac side, the interfacing inductors are used to filter high frequency components of compensating currents.

The first harmonic load currents of positive sequence are transformed to DC quantities. The first harmonic load currents of negative sequence and all the harmonics are transformed to non-DC quantities and undergo a frequency shift in the spectrum.

The voltage regulator in the converter DC side is performed by a proportional–integral(P-I) controller. Its input is the capacitor voltage error (vdcref-vdc) and it regulates the first harmonic active current of positive sequence. It is possible to control the active power flow in the VSI and thus the capacitor voltage Vdc remains constant.

The dynamics of each VSC are modeled by solving differential equations governing 2-level inverter. The switching of the inverter is done by monitoring the reference and actual currents and comparison of error with the hysteresis band of hysteresis controller (HCC).

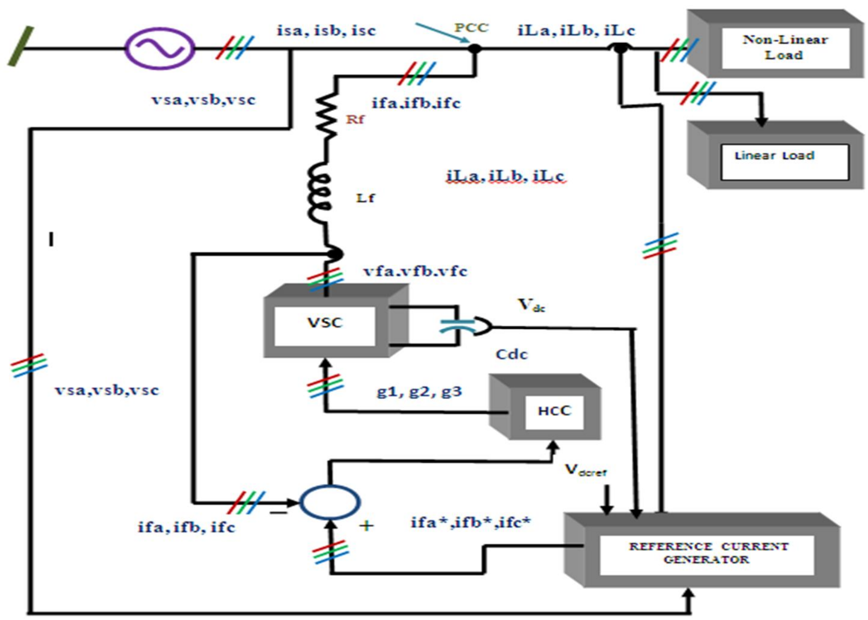

Fig.1 system configuration of DSTATCOM

III. Control strategies

A. Instantaneous p-q Theory

Instantaneous P-Q Theory was initially proposed by Akagi[4]. This theory is based on the transformation of three phase quantities to two phase quantities in α-β frame and the Instantaneous active and reactive power is calculated in this frame [4],[5]. Sensed inputs v_{sa} ,$v_{sb}$and v_{sc}&i_{La} ,i_{Lb} and i_{Lc} are fed to the controller and these quantities are processed to generate reference commands(i_{fa}^{*},i_{fb}^{*},i_{fc}^{*}) which are fed to a hysteresis based PWM current controller to generate switching pulses(g1,g2and g3) for DSTATCOM.

The system terminal voltages are given as

$$\left.\begin{aligned} v_{sa} &= V_m \sin(wt) \\ v_{sb} &= V_m \sin(wt - 2\pi/3) \\ v_{sc} &= V_m \sin(wt + 2\pi/3) \end{aligned}\right\} \quad (1)$$

and the respective load current are given as

$$\left.\begin{aligned} i_{La} &= \Sigma I_{Lan} \sin\{n(wt) - \theta_{an}\} \\ i_{Lb} &= \Sigma I_{Lbn} \sin\{n(wt - 2\pi/3) - \theta_{bn}\} \\ i_{Lc} &= \Sigma I_{Lcn} \sin\{n(wt + 2\pi/3) - \theta_{cn}\} \end{aligned}\right\} \quad (2)$$

In a, b and c coordinates a,b and c axes are fixed on the same plane apart from each other by 2π/3. These phasors can be transformed into α-β coordinates using Clarke's transformation as follows.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} (4)$$

Where α and β axes are the orthogonal coordinates . Conventional instantaneous power for three phase circuit can be defined as

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (5)$$

Where p is equal to conventional equation

$$p = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \quad (6)$$

Similarly, the instantaneous reactive power is defined as

$$q = v_\beta i_\alpha - v_\alpha i_\beta \quad (7)$$

Therefore in matrix form, instantaneous real and reactive power are given as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

The α-β currents can be obtained as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (9)$$

Where $\Delta = v_\alpha^2 + v_\beta^2$

Instantaneous active and reactive powers p and q can be decomposed into an average (dc) and oscillatory component

$$\left.\begin{aligned} p &= \bar{p} + \tilde{p} \\ q &= \bar{q} + \tilde{q} \end{aligned}\right\} \quad (10)$$

Where $\bar{p}$ and $\bar{q}$ are the average dc part and $\tilde{p}$ and $\tilde{q}$ are the oscillatory (ac) part of these real and reactive instantaneous power. Reference currents are calculated to compensate the instantaneous oscillatory component of the instantaneous active and reactive power. Therefore the reference compensating currents $i_{f\alpha}^{*}$ and $i_{f\beta}^{*}$ in α-β coordinate can be expressed as

$$\begin{bmatrix} i_{f\alpha}^{*} \\ i_{f\beta}^{*} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_{\alpha} & v_{\beta} \\ v_{\beta} & -v_{\alpha} \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix} \quad (11)$$

The oscillatory part of real power p and reactive power q is obtained by using 4^{th} order low pass Butterworth filter of cut-off frequency 25 Hz.

These currents can be transformed in abc quantities to find reference currents in a-b-c coordinates using reverse Clarke's transformation.

$$\begin{bmatrix} i_{fa}^{*} \\ i_{fb}^{*} \\ i_{fc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{f\alpha}^{*} \\ i_{f\beta}^{*} \end{bmatrix} \quad (12)$$

B. Synchronous Reference frame Method (SRF)

In this method Load current signal are transformed into conventional rotating frame d-q where θ is the transformation angle. In SRF θ is time varying angle that represents the angular position of the reference frame which is rotating at constant speed in synchronism with three phase ac voltage. There is no need supply voltage information for SRF based controller. However the phase position angle must be determined using voltage information.

This theory is based on the transformation of currents in synchronously rotating d-q frame [6],[7],[8]. Voltage signals are processed by the PLL[9] to generate the unit vectors. Current signals are transformed into d-q frame and then filtered .Then compensating current transformed back to a-b-c frame and fed to hysteresis current controller [10] for switching pulse generation.

The current components are transformed into α-β coordinates and using θ as a transformation angle again transformed from α-β to d-q frame with help of park's transformation.

$$\begin{bmatrix} i_{d} \\ i_{q} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \quad (13)$$

SRF controller extracts the oscillating part of i_d and i_q by use of a low pass Butterworth filter. The extracted compensating currents i_{fd}^{*} and i_{fq}^{*} are transformed back in to α-β frame using reverse park's transformation.

$$\begin{bmatrix} i_{f\alpha}^{*} \\ i_{f\beta}^{*} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{fd}^{*} \\ i_{fq}^{*} \end{bmatrix} \quad (14)$$

Then these reference currents are transformed back to a-b-c coordinates.

$$\begin{bmatrix} i_{fa}^{*} \\ i_{fb}^{*} \\ i_{fc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{f\alpha}^{*} \\ i_{f\beta}^{*} \end{bmatrix} \quad (15)$$

C. Modified Synchronous Reference frame Method(MSRF)(id-iq)

In this method the compensating currents are obtained from instantaneous active and reactive currents id and iq of the non-linear load [11]. However the dq load currents are derived from a synchronous reference frame based on the transformation where θ represent the voltage vector angle.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (16)$$

The transformation angle is sensitive to voltage harmonics and unbalanced voltage sources, therefore dθ/dt may not be constant.
Due to geometric relation

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{\Delta}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (17)$$

Where $\Delta = v_\alpha^2 + v_\beta^2$

One of the advantages of this method is that the θ angle is calculated directly from the main voltages and thus enables to be frequency independent. Avoiding the use of PLL it can be achieved a large frequency operating range limited by the cut- off frequency of VSI. Furthermore the synchronization problems with unbalanced non-sinusoidal mains voltages are also avoided. Performing the elimination of the average current components by high pass filter the compensating reference current i_{fd}^* and i_{fq}^* are obtained.
Then the compensating reference current is obtained in α-β coordinates.

$$\begin{bmatrix} i_{f\alpha}^* \\ i_{f\beta}^* \end{bmatrix} = \frac{1}{\sqrt{\Delta}} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{fd}^* \\ i_{fq}^* \end{bmatrix} \qquad (18)$$

Then these reference currents are transformed back to a-b-c coordinates.

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{f\alpha}^* \\ i_{f\beta}^* \end{bmatrix} \qquad (19)$$

D. Instantaneous Symmetrical Components Theory

The objective of this theory[12] to make source current balanced and harmonic free.

So $i_{sa} + i_{sb} + i_{sc} = 0$ (20)

The positive sequence voltage to a phase is

$$V^+ = \frac{1}{\sqrt{3}}(v_{sa} + a v_{sb} + a^2 v_{sc}) \qquad (21)$$

Where $a = e^{j2\pi/3}$. The angle of vector of +ve sequence

$$\angle\{v_{sa} + a v_{sb} + a^2 v_{sc}\} = \angle\{i_{sa} + a i_{sb} + a^2 i_{sc}\} + \phi \qquad (22)$$

Where $\phi = \angle(V^+) = \tan^{-1}\left\{ \dfrac{\frac{\sqrt{3}}{2} v_{sb} - \frac{\sqrt{3}}{2} v_{sc}}{v_{sa} - \frac{1}{2} v_{sb} - \frac{1}{2} v_{sc}} \right\}$ (23)

$$(v_{sb} - v_{sc} - 3\beta v_{sa}) i_{sa} + (v_{sc} - v_{sa} - 3\beta v_{sb}) i_{sb} + (v_{sa} - v_{sb} - 3\beta v_{sc}) i_{sc} = 0 \qquad (24)$$

Where $\beta = \dfrac{\tan\phi}{\sqrt{3}}$

The source deliver power must equal to the average of active power i.e.

$$v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} = p_{lav} \tag{25}$$

From the above relation

$$\begin{bmatrix} 1 & 1 & 1 \\ (v_{sb}-v_{sc}-3\beta v_{sa}) & (v_{sc}-v_{sa}-3\beta v_{sb}) & (v_{sa}-v_{sb}-3\beta v_{sc}) \\ v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ p_{lav} \end{bmatrix} \tag{26}$$

The source reference currents are obtained by solving the above equation (25),

$$i_{sa}^{*} = \frac{v_{sa} + (v_{sb} - v_{sc})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav} \tag{27}$$

$$i_{sb}^{*} = \frac{v_{sb} + (v_{sc} - v_{sa})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav} \tag{28}$$

$$i_{sc}^{*} = \frac{v_{sc} + (v_{sa} - v_{sb})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav} \tag{29}$$

In the above relation β represents the power factor co-efficient proportionate to reactive power. Finally under balanced and unit power factor

$$i_{fa}^{*} = i_{La} - i_{sa}^{*} = i_{La} - \frac{v_{sa}}{\Delta s}(p_{lav} + p_{loss}) \tag{30}$$

$$i_{fb}^{*} = i_{Lb} - i_{sb}^{*} = i_{Lb} - \frac{v_{sb}}{\Delta s}(p_{lav} + p_{loss}) \tag{31}$$

$$i_{fc}^{*} = i_{Lc} - i_{sc}^{*} = i_{Lc} - \frac{v_{sc}}{\Delta s}(p_{lav} + p_{loss}) \tag{32}$$

Where $\Delta s = v_{sa}^2 + v_{sb}^2 + v_{sc}^2$

Where p_{lav} is the average load power and p_{loss} is the losses in VSI which are computed as follows

$$p_{lav} = \frac{1}{T}\int (v_{sa}i_{La} + v_{sb}i_{Lb} + v_{sc}i_{Lc})dt \tag{33}$$

$$p_{loss} = k_p(v_{dcref} - v_{dc}) + k_i \int (v_{dcref} - v_{dc})dt \tag{34}$$

Where v_{dcref} and v_{dc} are the reference and actual capacitor voltage.

E. Average unit power factor theory(AUPF)[13]

The source must supply the sinusoidal currents in phase with the voltages.

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \frac{p_{lav}}{V^2} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{35}$$

$$p_{lav} = \frac{1}{T}\int (v_{sa}i_{La} + v_{sb}i_{Lb} + v_{sc}i_{Lc})dt \tag{36}$$

$$V^2 = \frac{1}{T}\int (v_{sa}v_{sa} + v_{sb}v_{sb} + v_{sc}v_{sc})dt \tag{37}$$

The compensator current are derived as $i_c = i_L - i_s$

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} - \frac{p_{lav}}{V^2} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{38}$$

The compensator reference currents can be compared with actual compensator currents pass through the hysteresis band controller which generates gate pulses for voltage source converter of DSTATCOM.

IV. PERFORMANCE INDICES

Total harmonic distortion**:**

The total harmonic distortion (THD) [14]is used to define the effect of harmonics on the power system voltage. It is used in low-voltage, medium-voltage, and high-voltage systems. It is expressed as a percent of the fundamental and is defined as

$$\mathrm{THD(voltage)} = \sqrt{\frac{\textit{sum of all squares of amplitude of harmonic voltages}}{\textit{square of the amplitude of fundamental voltage}}} \cdot 100\%$$

$$THD(voltage) = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} \tag{39}$$

$$\mathrm{THD(current)} = \sqrt{\frac{\textit{sum of all squares of amplitude of harmonic currents}}{\textit{square of the amplitude of fundamental current}}} \cdot 100\%$$

$$THD(current) = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_1} \tag{40}$$

According to IEEE-519 the permissible limit for distortion in the signal is 5%.

V. RESULTS AND DISCUSSION

To investigate the performance of the DSTATCOM for five control strategies, simulations are performed on matlab platform . A three phase three wire distribution system with parameters given below is considered for simulation.

System Parameters:

Supply voltage : 50Vrms(L-N),50Hz, three phase balanced
Sourceimpedance:Rs=0.1Ω,Ls=.5mH
Nonlinear load: Three phase full bridge diode rectifier .
DCstorage Capacitor Cdc=2000μF
Interface inductor Lf=5mH ,Rf=0.1Ω
DC Link voltage Vdc=100V
Hysteresis band=0.25A
Unbalanced Load:Za=67+j31.42Ω,
Zb=37+j18.85Ω
Zc=28.5+j12.56Ω

The performance of the control algorithm is evaluated based on two different cases.

Case1- Balanced Source and balanced Non-Linear load

Case2- Balanced Source and Unbalanced Non-linear load.

The simulation results for case 2(fig.2a- fig.2e) of best performance achieved algorithm (MSRF Method) are demonstrated here.

Case 2
MSRF Method(id-iq)

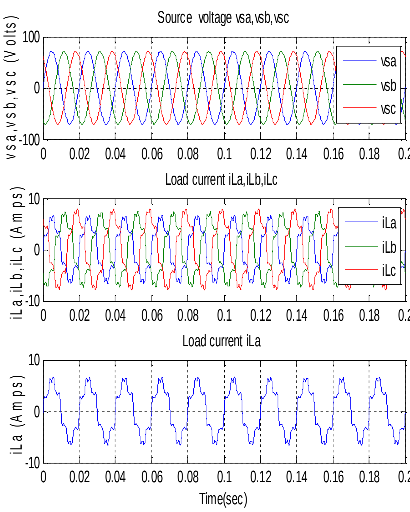

Fig.2a Source Voltage phase a ,b,c, Load Currentt phase a,b,c and Load current phase a

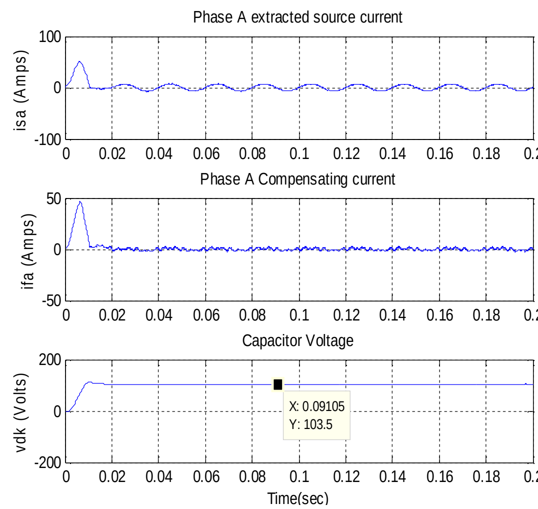

Fig. 2b Phase A extracted Source current, Compensating current and DC link Capacitor Voltage

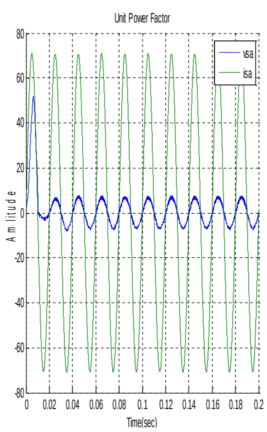

Fig. 2c Unit power factor of compensated Load

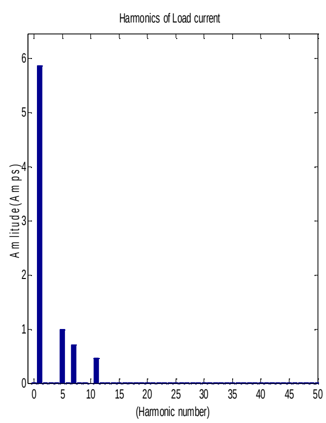

Fig. 2d Harmonics of Load current current phase **a**

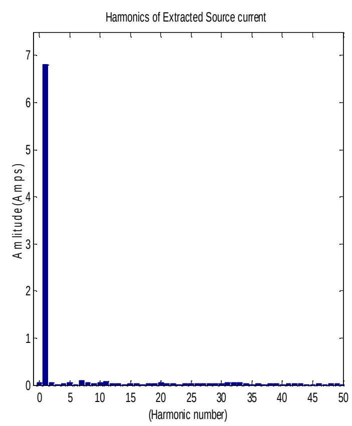

Fig. 2e Harmonics of extracted Source current phase a

In **case 1** the source is assumed to be sinusoidal and balanced whereas the load is considered as non-sinusoidal and balanced with load as six pulse diode full bridge rectifier. Before compensation the THD of load current is found to be **22.2914%.** After compensation the THD for different control strategies are listed in the T**able1.**

In **case 2** the source is balanced and sinusoidal but the load is unbalanced non sinusoidal .The THD of the load current for phase a after compensation is summarized in **Table 1.**Fig. 3 demonstrates the comparison chart of different control strategies for case1 and case 2.

The results demonstrated here are considered for phase a only.

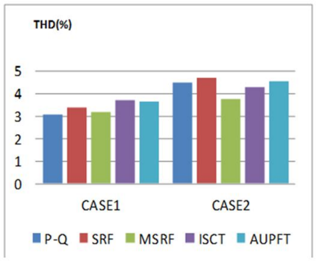

Fig. 3 Comparison chart of different control strategies

TABLE-1. COMPARISON

Control strategy	**THD(%)**	
	CASE-1	CASE-2
p-q	3.0748	4.4580
SRF	3.4017	4.6838
MSRF(id-iq)	3.1867	3.7313
ISCT	3.6914	4.2566
AUPFT	3.6482	4.5317

VI.CONCLUSION

In all cases it is observed that all the control strategies working fine and able to compensate the nonlinear unbalanced load successfully. The THD obtained here are within the limit of 5% prescribed by IEEE 519. From the above comparison chart it has been found that MSRF control strategyhas better performance for harmonic cancellation for balanced source and non-linear unbalanced load condition.

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